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Wear Characteristics of Three Rotor Coatings for Application to Brush Seals Operating in Liquid Hydrogen

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WEAR CHARACTERISTICS OF THREE ROTOR COATINGS FOR APPLICATION TO BRUSH SEALS OPERATING IN LIQUID HYDROGEN

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ABSTRACT

Three rotor coatings, chromium carbide, Teflon impregnated chromium, and zirconium oxide, were tested in liquid hydrogen with a 50.8 mm diameter brush seal made of Haynes 25 and a nominal initial radial interference of 129 μm at 35,000 and 65,000 rpm. These shaft speeds, respectively, generate surface velocities of 92 and 172 m/sec, simulating surface velocities expected in turbopumps for launch and upper-stage rocket engines. Differential pressures were up to 1.21 MPa across the seal. Comparisons of coating wear are made to a baseline Inconel-718 rotor. Bristle wear and material transfer results are also presented.

INTRODUCTION

The low leakage and good stability characteristics of brush seals make it an attractive candidate for use in advanced rocket engine turbopumps. The reusability desired for turbopumps of future rocket engines, however, will require good tribomaterials because brush seals are compliant, contacting seals, designed to have an interference fit (Ref 1).

There has been some effort to evaluate tribomaterials for brush seals, but the focus has been mainly on seal applications at high temperature and high speed conditions found in gas turbine engines (Ref. 2). Previous efforts conducted by NASA to develop brush seals for cryogenic applications have primarily investigated their low leakage performance (Ref. 3). The results reported in reference 3 reveal the importance of selecting good tribomaterials. Brush seals made of Haynes 25 bristles exhibited severe wear, damage, and excessive material transfer to an uncoated Inconel-718 seal runner when tested in liquid hydrogen. NASA also conducted a joint effort with Rocketdyne to test a brush seal that used a ceramic coated seal runner, but the testing was limited to liquid nitrogen which does not fully simulate the environment of rocket engine turbopumps (Ref. 4).

To identify suitable tribomaterials for cryogenic brush seals, the NASA Lewis Research Center evaluated several different seal runner coatings using a cryogenic seal tester. Three seal runner coatings, chromium carbide, Teflon impregnated chromium and zirconium oxide, were tested with brushes made of Haynes 25 bristles in liquid hydrogen and at shaft speeds simulating the environment and surface velocities of launch and upper-stage rocket engine turbopumps. Uncoated seal runners were also tested for comparison. Wear data and material transfer results for the runner coatings and brush bristles are presented.

EXPERIMENTAL METHODS

The cryogenic brush seal tester shown in Figure 1 was used to evaluate coated seal runners under conditions similar to those found in rocket engine turbopumps and to compare them to an uncoated Inconel-718 seal runner. Three seal runner coatings: chromium carbide, Teflon impregnated chromium, and zirconium oxide, were selected for their wear resistance. Teflon impregnated chromium also offers self-lubrication. The coatings were applied to seal runners made of Inconel-718 to provide a nominal initial radial interference of 129 μm when matched with a 50.8 mm diameter brush made of Haynes 25 bristles. A typical brush seal is pictured in Figure 2, and the nominal brush geometry is given in Table I. As shown in Figure 2, brush seals consist of a pack of small diameter bristles (0.071 mm) held at an angle between two washers. The inner diameter of the back washer is smaller than the front washer to support the bristles when subjected to a pressure differential across the seal and restrict the axial flow area through the seal. The radial

distance between the back washer and rotor is called the fence height. The brush inner diameter is typically smaller than the rotor diameter creating an interference fit that allows the seal to maintain contact during rotor perturbations.

Two sets of brush seals were made with each type of material so that they could be tested separately at speeds of 35,000 and 65,000 rpm, generating 92 and 172 m/sec surface velocities, respectively. Table II presents the pertinent seal runner properties including coating deposition process, thickness, surface finish and hardness, as well as interference fit and test speed. Comparison between coatings could be made since all brush seals started with about the same interference fit (see Table II) and underwent similar test profiles. Figures 3 and 4 display the nominal test profiles for the seals tested at the two speeds. Maximum differential pressure across the seals was 1.21 MPa. Each brush seal was subjected to the test profile twice to provide intermediate wear data. The brush seals with the Teflon impregnated chromium and chromium carbide coated runners tested at 65,000 rpm were subjected to a third test to accumulate additional run duration because of their good tribological performance.

Seal runner wear was quantified using a surface profilometer. Surface traces were made perpendicular to the brush track at four locations equally spaced around the circumference of the seal runner. Scanning Electron Microscopy (SEM) with Back Scatter Detector (BSE) and X-Ray Energy Dispersive Elemental Analysis (EDAX) provided information on material transfer between the brush and seal runner. The SEM/BSE provides qualitative chemical analysis by contrasting elements of different atomic numbers with varying signal intensities. The qualitative information is captured on micrographs as different brightness levels; lower atomic number elements appear darker while higher atomic number elements appear lighter. The SEM/EDAX provides elemental identification. Bristle tip wear was determined using an optical comparator. The inner radius of the brushes was measured at multiple locations equally spaced around the circumference before and after each test to determine wear. Brush seal wear was based on the average of the measured values. The tribological performance of the brush seal material combinations are presented and discussed in-turn, beginning with the baseline case, the uncoated Inconel-718 seal runner.

UNCOATED INCONEL-718 SEAL RUNNER

Two uncoated Inconel-718 seal runners were tested as a baseline. One was tested to a top speed of 35,000 rpm for approximately 43 minutes and accumulated 213 kilometers of linear sliding distance. The other one was tested to a speed of 65,000 rpm for approximately 38 minutes and accumulated 300 kilometers of linear sliding distance. Linear sliding distance is calculated using the seal runner radius and the actual rotational speed profile. Similar to the results reported in reference 3, both uncoated seal runners exhibited significant amounts of bristle material deposited on the surface which accumulated during the first test since the profilometer trace of the seal runner surface after the second test showed negligible change. The final surface profile shown in Figure 5 reveals several peaks located across the wear track that rise above the nominal surface profile, indicating a buildup of material. The SEM/EDAX analysis confirmed the deposit of bristle material on the seal runner by identifying the presence of tungsten and cobalt which are present in the bristle material, Haynes 25, and not in the seal runner material, Inconel-718. Figure 6 shows the micrograph of the whole track width taken with the SEM using the Back-Scatter Detector. Tungsten and cobalt, which appear lighter in the micrograph, were smeared onto the seal runner as evident from the higher magnification micrograph shown in Figure 7. Such transfer of metal from the bristle to the runner is undesirable because it promotes galling due to like-on-like metal contact (Ref. 2).

The brushes exhibited significant bristle wear and the one tested to the higher speed incurred bristle damage. Figure 8 displays the damaged bristles bent in different directions. In addition, some bristles located adjacent to the back washer had flat spots worn on the side facing the washer, which was presumably caused by the bristles rubbing against the washer. Such evidence suggest that large runner orbits occurred. In fact, a large 0.254 mm diameter runner orbit was briefly observed for the brush seal tested at 65,000 rpm. For the brush seal tested to 35,000 rpm, the bristle tips wore 64 μm. Slightly less wear, 41 μm, was measured on the brush tested to 65,000 rpm, which may be due to the slightly lower initial interference fit and softer surface finish of the seal runner. The seal runner tested to 65,000 rpm had a 129 μm interference fit and a 38 Rc hardness as compared to 135 μm interference fit and 46 Rc for the one tested to 35,000 rpm as shown in Table II.

CHROMIUM CARBIDE COATED SEAL RUNNER

Chromium carbide with Haynes 25 was selected for evaluation based on the good performance reported in reference 2. The chromium carbide coated runners did not experience bristle material buildup like the uncoated Inconel-718 seal runner. Instead, it incurred some wear at both 35,000 and 65,000 rpm. At the lower speed the coating developed a 3 to 6 μm deep wear track and a deposit of material at the edge of the track on the low pressure side of the seal (downstream edge) as displayed in Figure 9. The seal accumulated 223 kilometers of linear sliding distance over the 51 minutes of test duration. In contrast, the seal runner tested at the higher speed exhibited a 7 to 20 μm deep wear track and a 3 to 10 μm high deposit of material at the high pressure side as shown in Figure 10. On both seal runners, the wear occurred during the first test since there was little difference in surface traces taken after the additional tests. The deposited material consisting of tungsten and cobalt is from the bristles as evident from SEM/BSE micrograph displayed in Figure 11, and EDAX analysis. Tungsten and cobalt, which appear lighter on the micrograph, were heavily smeared at the one edge of the track and sparsely deposited over the rest of the track. The seal tested to 65,000 rpm accumulated 450 kilometers of linear sliding distance and 58 minutes of test duration.

The chromium carbide coated brush seal exhibited less bristle wear than the uncoated brush seal. The brush tested at the higher speed wore 38 μm as compared to 41 μm for the uncoated brush seal even though it accumulated one and half times the sliding distance of the uncoated brush seal. The brush seal tested at the lower speed incurred 25 μm of wear which is less than half the bristle wear of the uncoated brush seal. The reduced bristle wear may be due to the coating inhibiting the transfer of bristle material to the seal runner, thus preventing adhesive wear caused by material galling.

TEFLON IMPREGNATED CHROMIUM COATED SEAL RUNNER

The Teflon impregnated chromium is a good candidate for the brush seal application because it is a commercially available coating developed as a wear resistant and low-friction surface. The brush made a visible track in the coating at both speeds, but coating wear was immeasurable on the runner tested at 35,000 rpm as apparent from the surface profile trace displayed in Figure 12. The brush accumulated 28 minutes run time and 86 kilometers of linear sliding distance. The runner tested at 65,000 rpm, which accumulated 66 minutes duration and 577 kilometers linear sliding distance, incurred only a slight wear track measuring 2 to 12 μm deep. The wear occurred during the first test like the chromium carbide coated brush seal. The minimum and maximum wear track depth, which are shown in Figures 13 and 14, respectively, occurred 180 degrees apart. Thus, it is suspected that rotor unbalance and/or runout may have caused this variation. Figure 15 displays the SEM/BSE micrograph of the track for the seal tested at 65,000 rpm, and Figure 16 shows an enlargement of the track's edge. EDAX analysis identified the black spots found on either side of the track as fluorine, a major element of Teflon. In the brush track area, the Teflon was practically gone as evident from the absence of black spots present in this area. In contrast, some Teflon remained in the track on the seal runner tested at the lower speed as apparent from Figures 17 and 18. In addition, small quantities of tungsten and cobalt were found at the edge of the track of both seal runners as apparent from Figures 16 and 18, indicating the transfer of bristle material. Teflon was not found on the bristle tips.

At the lower speed, the brush exhibited negligible wear. The brush tested at 65,000 rpm, however, showed 56 μm of wear on the bristle tips that seemed to occur during the third test. The results suggest that the Teflon provides lubrication, but it is a self-sacrificing protective film. Bristle wear begins once the Teflon layer is removed. Consequently, the viability of this coating is dependent on the specific operation conditions of the intended application.

ZIRCONIUM OXIDE COATED SEAL RUNNER

A zirconium oxide coating was selected because it showed good wear performance in brush seal testing conducted at Rocketdyne under a joint effort with the NASA Lewis Research Center (Ref 4). The tests, however, were conducted in liquid nitrogen.

The zirconium coating incurred significant wear while the bristles incurred only slight wear . The seal runner tested at 35,000 rpm, which was tested for approximately 47 minutes and accumulated 222 kilometers of linear sliding distance, exhibited a 70 to 90 μm deep wear track as shown in Figure 19, and the bristles wore 5 μm. The seal runner tested at 65,000 rpm exhibited similar wear, measuring 45 to 85 μm deep as shown in Figure 18, but the bristles incurred

greater wear measuring 18 μm. The seal tested to high speed accumulated similar test duration of 48 minutes, but it accrued significantly more linear sliding distance of 337 kilometers. At both speeds bristle material transferred to the seal runner as evident from the presence of tungsten and cobalt on the runner. In addition, there is evidence that some zirconium transferred to the bristles at both speeds. In contrast to the other coatings, the ceramic coating continued to wear during the second test.

The poor wear performance of the coating raises suspicion about the quality of the ceramic coating considering the good results reported in reference 4. Ceramic coating quality can be greatly affected by raw material properties and deposition process. Of particular concern with the ceramic coatings tested is the measured 62-67 Rc hardness (see Table II) which is significantly lower than the 79 Rc hardness typically quoted for this ceramic (Ref 5). The low hardness may indicate high porosity which will significantly reduce its wear resistance as stated in reference 5.

CONCLUDING REMARKS

Three seal runner coatings, chromium carbide, Teflon impregnated chromium, and zirconium oxide, were tested in liquid hydrogen at 35,000 and 65,000 rpm with separate 50.8 mm diameter brush seals made of Haynes 25 bristles to provide a nominal initial radial interference of 129 μm. Two bare Inconel-718 rotors were also tested as a baseline.

The test results revealed significant differences between the wear characteristics of the uncoated and coated seal runners. At both speeds the brush seal with the bare Inconel-718 seal runner exhibited significant bristle wear with excessive material transferring to the runner surface. In contrast, the coated seal runners inhibited the transfer and deposit of bristle material. Chromium carbide coating showed only small quantities of bristle material transferring to its surface. The Teflon impregnated chromium coating also inhibited material transfer and provided some lubrication. The coating, however, is self-sacrificing. The Teflon remained present on the low speed runner, but it was completely removed from the high speed brush seal, which was tested for a considerably longer test duration. The tests of the Teflon coating, however, revealed the importance of using a lubricating and low friction coating for brush seals to reduce bristle and seal runner wear. The zirconium oxide coating exhibited the greatest amount of coating wear, while the brushes incurred only slight wear. Further testing of ceramics is recommended before final judgement on the viability of ceramic coated brush seals because of the contrast between the results reported in reference 4 and the results presented herein. Strictly based on the results presented hereinabove, the chromium carbide and Teflon impregnated chromium coatings were considered preferable to the uncoated Inconel-718 and zirconium oxide coatings because of their good wear resistance and characteristics to inhibit bristle material wear and transfer to the seal runner.

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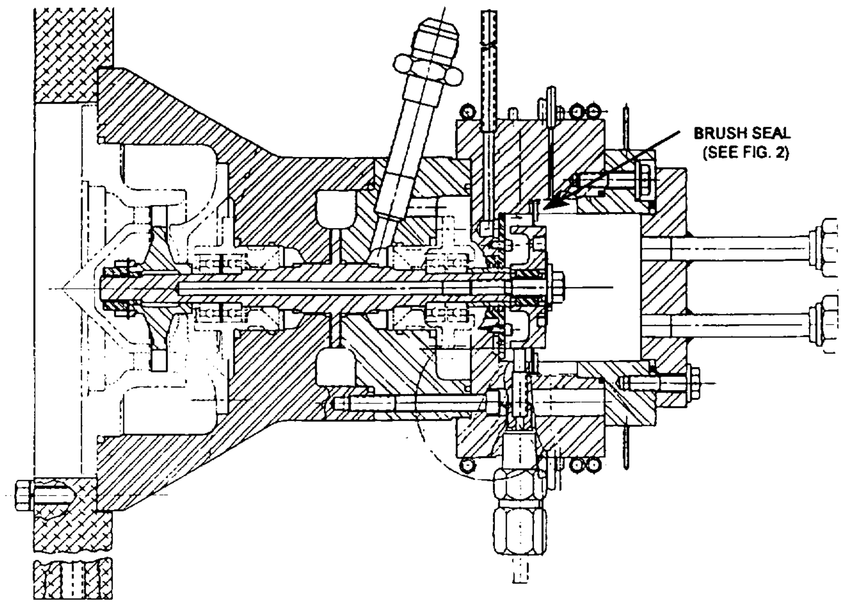

FIGURE 1. CROSS SECTION OF CRYOGENIC BRUSH SEAL TESTER

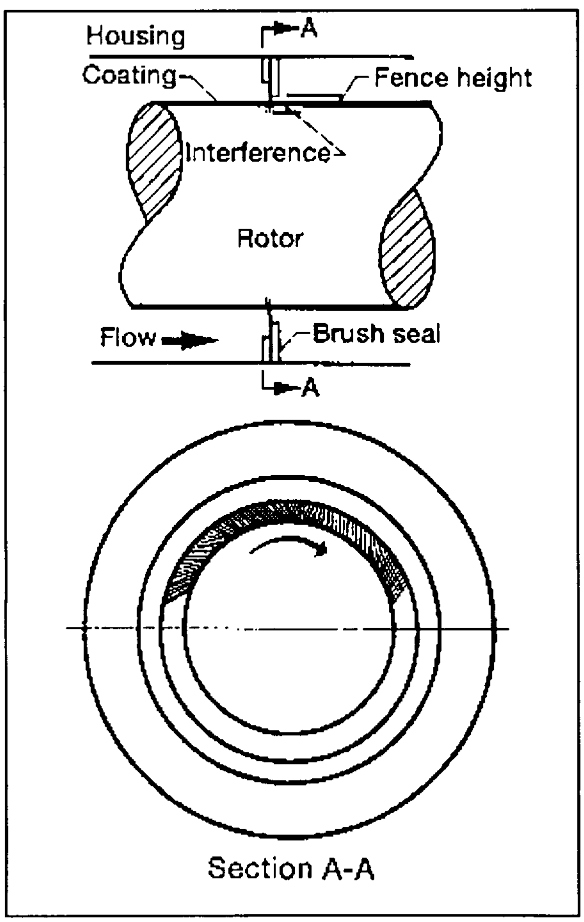

FIGURE 2. BRUSH SEAL

TABLE I. NOMINAL GEOMETRY

ROTOR:		
	OUTSIDE DIAMETER	50.8 mm
	MATERIAL	INCONEL 718
	COATINGS	CrC Cr+TEFLON ZrO2
BRUSHES:		
	MANUFACTURER	TECHNETICS
	OUTSIDE DIAMETER	71.6 mm
	FRONT WASHER I.D.	61.0 mm
	AXIAL THICKNESS	3.6 mm
	BACK WASHER I.D.	51.4 mm
	BRISTLE ANGLE	40 DEGREES
	BRISTLE DIAMETER	0.07 mm
	PACKING DENSITY	120 BRISTLE/ mm-CIRCUMF.
	WASHER MATERIAL	HASTELLOY-X
	BRISTLE MATERIAL	HAYNES-25

TABLE II. SEAL RUNNER PROPERTIES

SEAL RUNNER COATING	COATING DEPOSITION PROCESS	COATING THICKNESS (mm)	SURFACE FINISH (RMS-μm)	COATING HARDNESS (Rc)	INTER-FERENCE FIT (μm)	TEST SPEED (rpm)
INCONEL-718 (UNCOATED)	-	-	.3	46	135	35,000
INCONEL-718 (UNCOATED)	-	-	.3	38	129	65,000
Cr C	Plasma sprayed	100	.3	67	120	35,000
CrC	Plasma sprayed	100	.3	66	128	65,000
Cr+Teflon	Cr electro-deposit and ground. Then Teflon impregnated into fissures created by chemically etching the Cr.	50.8	.6	50	130	35,000
Cr+Teflon	Cr electro-deposit and ground. Then Teflon impregnated into fissures created by chemically etching the Cr.	50.8	.9	60	130	65,000
ZrO2	Plasma sprayed onto 100 μm thick AMI 973 bond coat	203	.4	67	132	35,000
ZrO2	Plasma sprayed onto 100 μm thick AMI 973 bond coat	203	.4	62	132	65,000

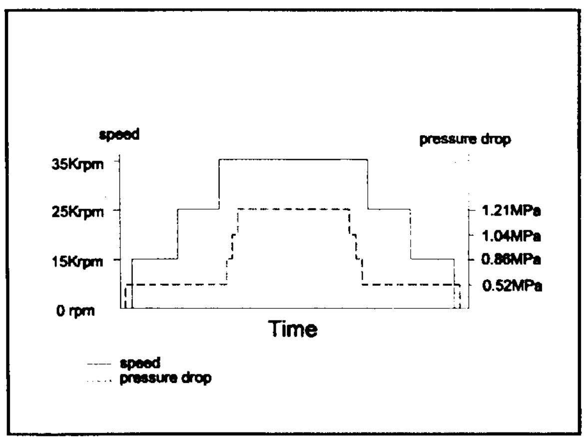

FIGURE 3. TEST PROFILE FOR SEALS TESTED TO 35,000 RPM.

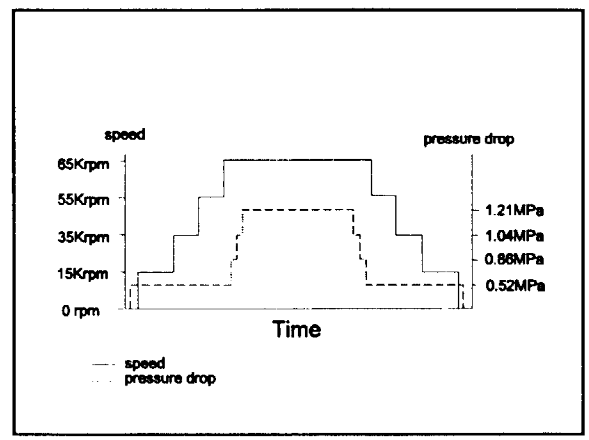

FIGURE 4. TEST PROFILE FOR SEALS TESTED TO 65,000 RPM.

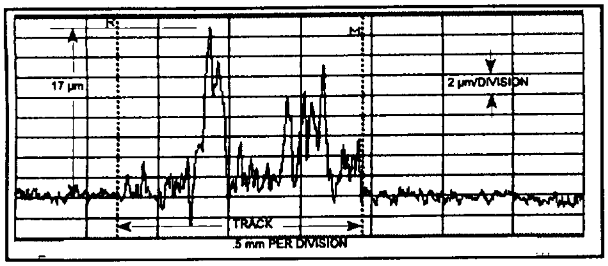

FIGURE 5. PROFILOMETER TRACE OF UNCOATED INCONEL-718 RUNNER TESTED AT 65,000 RPM.

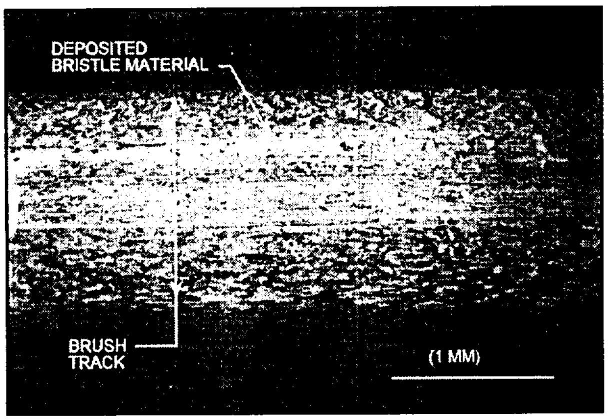

FIGURE 6. INCONEL-718 (UNCOATED) SEAL RUNNER TESTED AT 65,000 RPM.

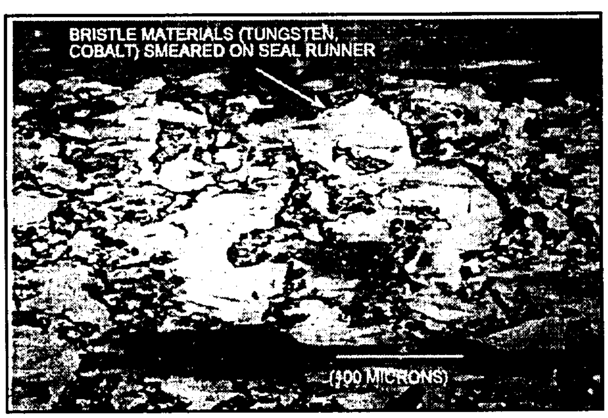

FIGURE 7. INCONEL 718 (UNCOATED) SEAL RUNNER TESTED AT 65,000 RPM.

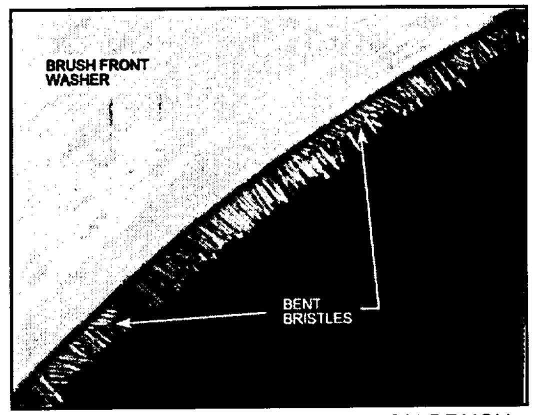

FIGURE 8. DAMAGED BRISTLES ON BRUSH WITH UNCOATED SEAL RUNNER TESTED AT 65,000 RPM.

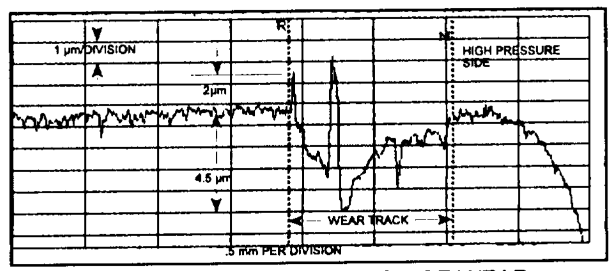

FIGURE 9. PROFILOMETER TRACE OF WEAR TRACK ON CHROMIUM CARBIDE COATED RUNNER TESTED AT 35,000 RPM.

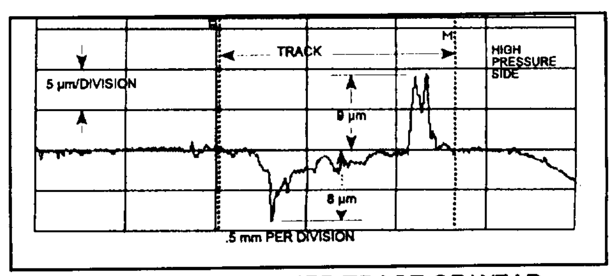

FIGURE 10. PROFILOMETER TRACE OF WEAR TRACK ON CHROMIUM CARBIDE COATED RUNNER TESTED AT 65,000 RPM.

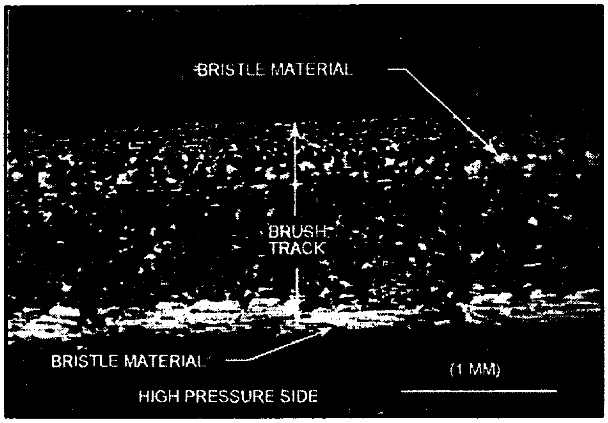

FIGURE 11. CHROMIUM CARBIDE COATED SEAL RUNNER TESTED AT 65,000 RPM.

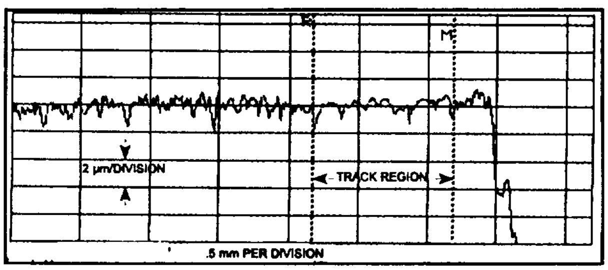

FIGURE 12. PROFILOMETER TRACE OF TEFLON IMPREGNATED CHROMIUM COATED RUNNER TESTED AT 35,000 RPM.

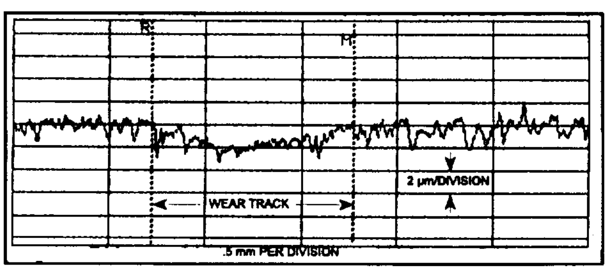

FIGURE 13. PROFILOMETER TRACE OF THE MINIMUM WEAR DEPTH ON THE TEFLON IMPREGNATED CHROMIUM COATED RUNNER TETED AT 65,000 RPM.

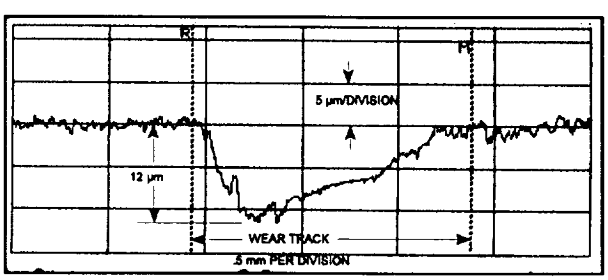

FIGURE 14. PROFILOMETER TRACE OF THE MAXIMUM WEAR DEPTH ON THE TEFLON IMPREGNATED CHROMIUM COATED RUNNER TESTED AT 65,000 RPM.

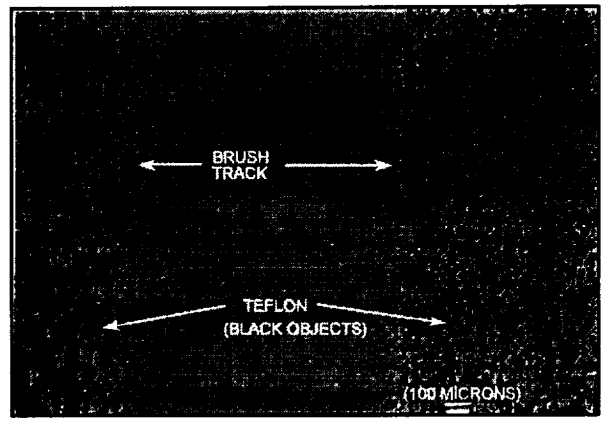

FIGURE 15. BRUSH TRACK ON THE TEFLON IMPREGNATED CHROMIUM COATED SEAL RUNNER TESTED AT 65,000 RPM.

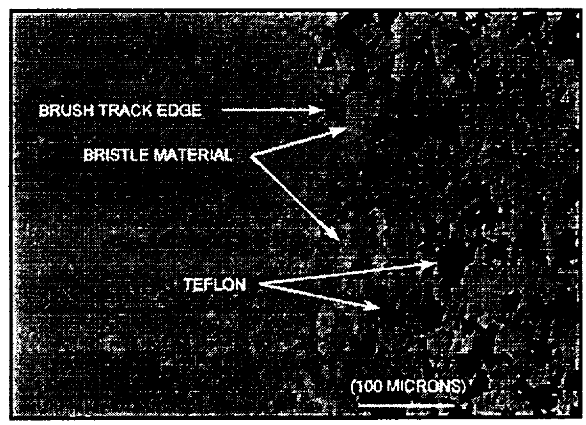

FIGURE 16. EDGE OF BRUSH TRACK ON THE TEFLON IMPREGNATED CHROMIUM COATED SEAL RUNNER TESTED AT 65,000 RPM.

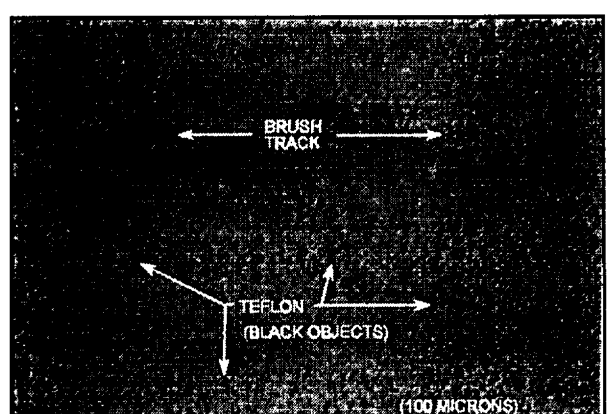

FIGURE 17. BRUSH TRACK ON TEFLON IMPREGNATED CHROMIUM COATED SEAL RUNNER TESTED AT 35,000 RPM.

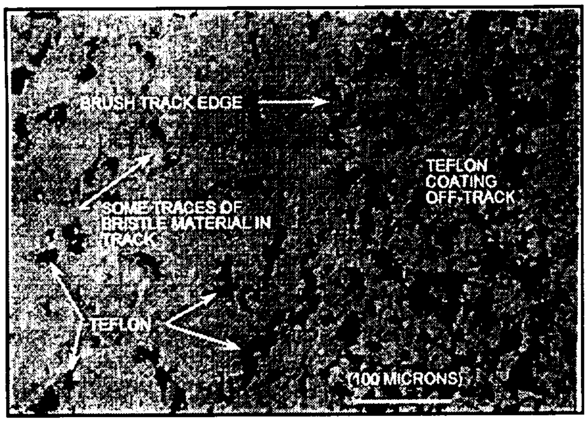

FIGURE 18. EDGE OF BRUSH TRACK ON TEFLON IMPREGNATED CHROMIUM COATED SEAL RUNNER TESTED AT 35,000 RPM.

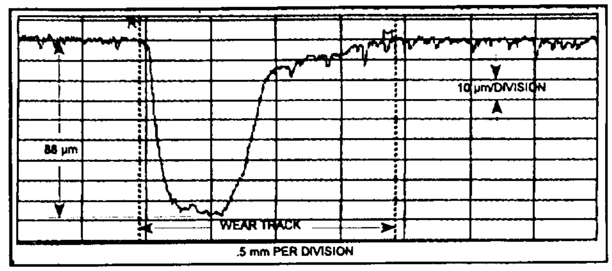

FIGURE 19. PROFILOMETER TRACE OF WEAR TRACK ON ZIRCONIUM OXIDE COATED RUNNER TESTED AT 35,000 RPM.

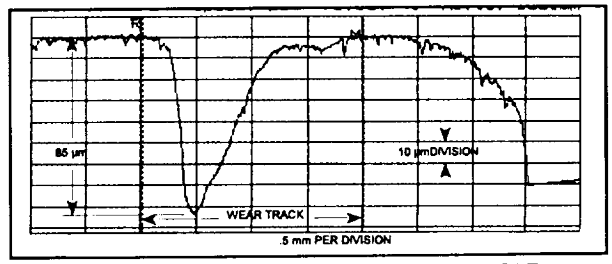

FIGURE 20. PROFILOMETER TRACE OF WEAR TRACK ON ZIRCONIUM OXIDE COATED RUNNER TESTED AT 65,000 RPM.

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